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A Study on Properties of Polymer-Based Additive Manufacturing

(Kajian Pencirian Sifat Bahan Pembuatan Aditif Berasaskan Polimer)

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ABSTRACT

In recent years, increasing interest in 3D Printing (3DP) has meant that printer usage is not limited to industrial purposes only, but is also for domestic usage by hobbyists for their individual needs. Polymer-based part production can now even be conducted outside the traditional factory environment. However, low grade printers pose some drawbacks, such as lower heat for material fusion, uncontrolled open ambience and limited nozzle size. These reduce the mechanical and aesthetical qualities as compared to parts fabricated using industrial grade printers. The study aims to perform some quality comparisons between 3D printed polymeric parts fabricated by both industrial and low cost printers, and subsequently to prove the hypothesis that the industrial grade printed part has a more reliable surface quality and mechanical properties. Specimens were fabricated using each printer type (Fused Deposition Modelling (FDM) represents the low cost printer and the Multi Jet Printer (MJP) is used for the industrial grade) and later tested for hardness and surface roughness. Comparisons were then made between different fabricating methods and also based on a literature study according to the type of materials. The experiments showed that both the surface roughness and hardness for the plastic parts fabricated by the industrial grade printer were better than those made by the domestic printer, and showed a good agreement with the results in the literature study. Therefore, for highly durable parts, it is suggested that industrial grade printers are used. One point to conclude the study, Rapid Prototyping is possible by any machine, but for Rapid Manufacturing that requires higher durability, it is better to use an industrial grade printer.

Keywords: Additive Manufacturing; 3D Printing; Rapid Prototyping; Polymer

ABSTRAK

Beberapa tahun kebelakangan ini, percetakan 3D (3DP) semakin diminati dan penggunaanya yang meluas telah menyebabkan penggunaan pencetak bukan sahaja terhad kepada tujuan industri bahkan juga untuk kegunaan persendirian bagi mereka yang menjadikannya sebagai hobi. Penghasilan produk terutama yang berasaskan polimer kini boleh dihasilkan di luar kilang pembuatan seperti kebiasaannya. Namun pencetak gred rendah menunjukkan beberapa kelemahan seperti haba yang lebih rendah untuk pelakuran bahan, persekitaran yang terbuka dan tidak terkawal serta saiz muncung yang terhad. Ini mengurangkan kualiti mekanikal dan estetika berbanding yang dihasilkan dengan pencetak bergred industri. Kajian ini bertujuan untuk membandingkan beberapa kualiti antara produk polimer yang difabrikasi menggunakan pencetak kos rendah dan gred industri dan seterusnya membuktikan hipotesis bahawa hasil dari pencetak bergred industri mempunyai sifat mekanikal dan kualiti permukaan yang lebih baik dan dipercayai. Spesimen difabrikasi menggunakan dua jenis pencetak (FDM mewakili pencetak murah manakala MJP untuk pencetak gred industri) dan kemudiannya diuji untuk melihat sifat kekerasan dan kekasaran permukaan. Perbandingan kemudiannya dilakukan berdasarkan kaedah fabrikasi dan juga berdasarkan kajian literatur mengikut jenis bahan. Eksperimen menunjukkan produk yang dihasilkan dengan pencetak industri mempamerkan keputusan yang lebih baik bagi kedua-dua ujian yang dijalankan dan juga menepati keputusan kajian litaratur yang terdahulu. Oleh itu, bagi aplikasi yang memerlukan kebolehtahanan yang tinggi, adalah dicadangkan agar menggunakan pencetak professional. Sebagai kesimpulan, prototaip pantas boleh dilakukan dengan mana-mana jenis pencetak, namun bagi pembuatan pantas yang memerlukan ketahanan tinggi, adalah lebih baik jika menggunakan pencetak bergred industri.

Kata kunci: Pembuatan Tambahan; Cetakan 3D; Prototaip Pantas; Polimer

INTRODUCTION

Additive Manufacturing (AM), as defined by ASTM F42, is the process of joining materials to make objects from three-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies (ASTM 2013). Because the solid parts are made directly from 3D data, no part-specific moulds or tools are needed. Nowadays, 3D printing is readily available to the masses, with machine complexity and printing quality ranging from domestic consumer Do-It-Yourself (DIY) (Dawoud et al. 2016) grade equipment to high end industrial machinery. Part fabrication using AM is becoming more common in hobby and craft settings (Smith & Dean 2013). This study will be focusing on two AM technologies namely FDM and MJP.

FUSED DEPOSITION MODELLING (FDM)

FDM is one of the most popular additive manufacturing techniques and because of its straightforward working principle, as shown in Figure 1, it is a basic, yet fast-growing rapid prototyping (RP) technology. Using this process, parts of any geometrical shape can be built by deposition of material on a layer by layer and line by line basis (Huang & Singamneni 2014) based on 3D data. This has made FDM a very decent AM technique as compared to other systems which involve an array of lasers, powders, resins (Sood et al. 2010) and even metal based AM. FDM uses semi-solid polymeric materials, normally in thermoplastic filament in spool as feedstock, extruded through the nozzle and is made viscous (Faes et al. 2016) after being heated in chamber.

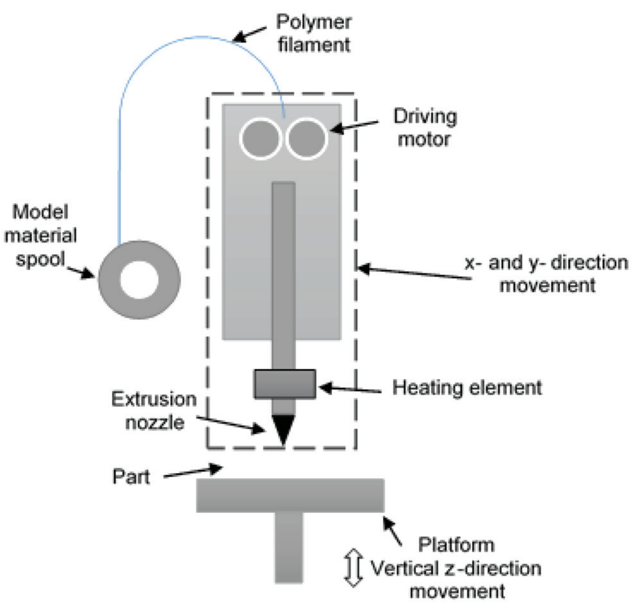

FIGURE 1. Basic working principle of FDM

Due to the building methodology, it is common that parts fabricated with FDM technology are anisotropic internally (Huang & Singamneni 2014) and have different properties on the outline and inside (Szykiedans & Credo 2016). Commonly used materials for FDM are a wide range of ABS (Novakova-Marcincinova & Kuric 2012) for high toughness and strength application, polylactic acid (PLA) for stiff and environmentally friendly materials, polyamide, polycarbonate, polyethylene, polypropylene and nylon for soft application, and HDPE for food grade compatible parts (Dawoud et al. 2016). If one is comparing two different technologies, FDM is very suitable to represent the low class AM due to its very basic building method.

MULTI JET PRINTING (MJP)

MJP is an additive manufacturing process, similar to inkjet printing, but there are multiple small holes at the print head. This process uses an ultraviolet curable photopolymer and during the process, the print head shuttles back and forth depositing material through each small jet to build each single layer. After each layer is dispensed, the process will be followed by a flash of ultraviolet light to cure the polymer. When one layer is completed, the platform (as shown in Figure 2) is lowered by a one-layer thickness and the next layer is built upon the previous layer. This process is repeated until the entire part is built. Other than the building material for the part, a support material is simultaneously deposited during the process and post-processing is required later on to remove the waxy support material by heating in an oven or furnace, leaving the finished printed part only.

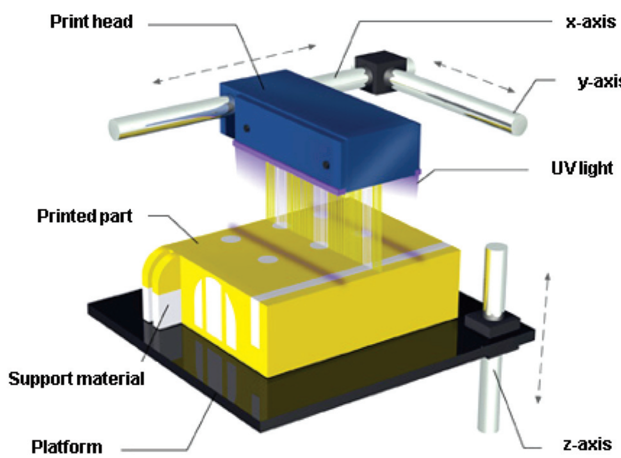

FIGURE 2. Basic working principle of MJP

The advantages of the MJP process include cost effectiveness, shorter build time and office friendliness. Because the print head jets such small droplets, MJP allows for details in parts that are extremely small and precise (Guo & Leu 2013). The commercial manufacturer of the MJP equipment is 3D Systems (Rock Hill, USA). Obviously, between MJP and FDM, MJP is more expensive, has a complex system and is usually for professional use.

Typically, domestic 3D printers (e.g. RepRap, Makerbot, Ultimaker, Fab@home) are based on FDM technology as this has the simplest working principle, is easy to maintain and handle, and is hassle free. Historically, in 1988, FDM was patented by Stratasys Incorporated and when the first patent expired in 2009, FDM came into the public domain where the technology is available commercially (Ford & Despeisse 2015) and is free to be utilised and innovated. Parts accuracy, as built by domestic printers, is the key issue. Meanwhile, for industrial printers, however, despite the higher quality being offered, there are contradictions to be considered, including higher costs, material restrictions and the complexity of the process parameters. For some applications, other than being easy to print, the question is how reliable is the quality of the parts coming from the domestic printers, especially the parts expected to perform in the long run? Is the durability comparable to those from an industrial machine? Comparisons between AM technologies are not necessarily made using the same material (Shah et al. 2016), because each technology comes with limited types and forms of materials, for example MJP must use ultraviolet curable material in the form of a liquid while FDM is in solid filament form.

The objective of this study is to compare the basic mechanical properties, part hardness and surface quality, which is the roughness of the printed parts, as fabricated by the industrial and the low cost printer, and from the insights it is subsequently intended to prove the hypothesis that the industrial grade printer will produce parts with more reliable quality and better mechanical properties than the lower grade one. The properties of the fabricated parts are characterised by the material and the manufacturing process, therefore it is vital to have some idea concerning how the manufacturing process may alter the material's properties (Ahmad et al. 2016).

MATERIALS AND METHODS

Overall, the materials and methods will be explained in detail. However, for quick understanding, Figure 3 summarises the methodology of the study.

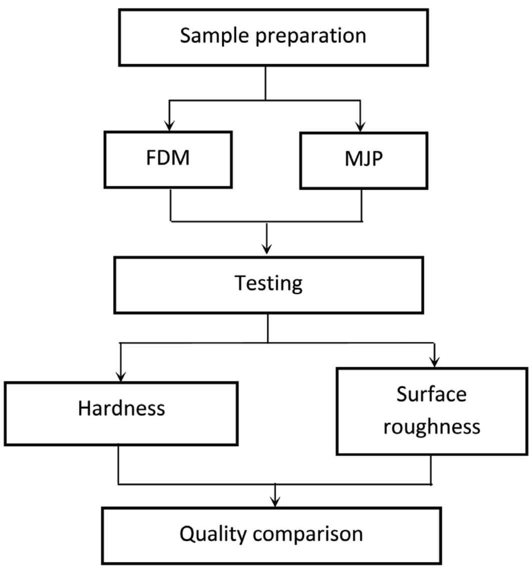

FIGURE 3. Flow chart of research methodology

SAMPLE PREPARATION

For both printers, Stereolithography (STL) files for the column models were created on Solidworks 2012 (Dassault Systèmes, Paris, France). The parts (which in the future study will undergo other testing including tensile strength) were made in a dog bone tensile bar shape according to ASTM 638 Type I, with a thickness of 6mm as shown in Figure 4.

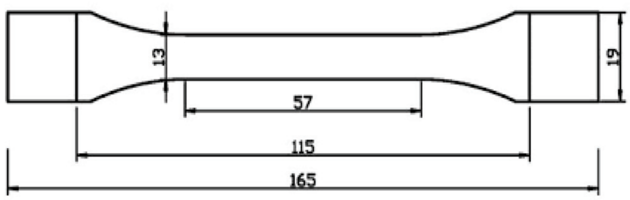

FIGURE 4. Part design

Parts were manufactured from PLA filament of diameter 2.85 mm, and the FDM machine used in this work is the Ultimaker 2+ as depicted in Figure 5. Default settings of extrusion temperature and speed were used as recommended by the manufacturer and the machine underwent a test run and calibration prior to the real printing process. For all of the PLA specimens, no post-processing was done and the testing was performed on the as-built sample

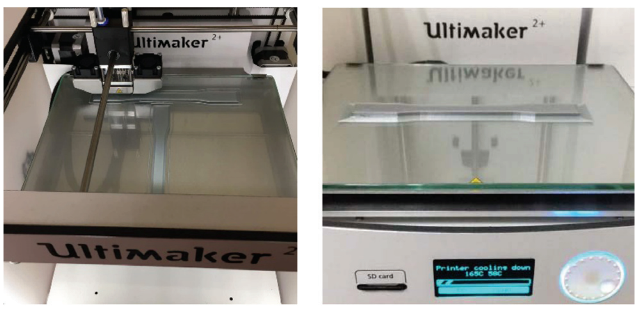

FIGURE 5. Parts fabrication using the FDM printer Ultimaker^{2+}

On the other hand, parts with a similar design were printed on a ProJet HD 3510 printer (3D Systems, Rock Hill, SC, USA). The printed components were made from non-porous urethane acrylate oligomers (acrylonitrile butadiene styrene, ABS). Similar tensile bar shaped parts were fabricated with a photopolymerisable polymer (VisiJet® M3 Crystal) using 3D Systems MJP technologies ProJet®3510SD. Post-processing was done on the sample printed by ProJet in order to remove the support wax by heating to 70°C in an oven.

PART PROPERTIES TESTING

To analyse the surface roughness, the average roughness (Ra) is considered and measured perpendicular to the lay direction using stationary Mohr Perthometer S2 apparatus as shown in Figure 6. A measuring probe with a radius of 2 µm was used to scan a straight track of 5.6 mm in the longitudinal direction at 0.5 mm/s. Taking into account the anisotropic features inherent in the AM fabricated part (Van

Hooreweder et al. 2013) several roughness readings were taken from different location on each part surface. From this, irregularities of roughness during printing, if any, will possibly be detected.

(a)

(b)

FIGURE 6. Surface roughness testings on (a) PLA and (b) ABS

Another mechanical property being tested is the part hardness. The digital Durometer, Future-Tech Rockwell hardness has been used with a 0.1mm indenter tip, 30° cone angle and 2.5 mm indenter length as per the ASTM D 2240 standards to measure the shore D scale hardness of the plastic ABS specimen. The hardness was measured randomly at five points, and because the additively manufactured part is made layer by layer, and is therefore anisotropic, all the measurements were taken from only one surface for each part, not from the side where the formation of layering takes place.

RESULTS AND DISCUSSION

COMPARISON OF PARTS HARDNESS

Five indentations were made for the Rockwell hardness test for each material, and the average value and standard deviation representing the part hardness are as shown in Table 1.

TABLE 1. Hardness of the PLA and ABS printed parts

	PLA	ABS
	7.4	26.0
	6.3	27.3
HRL_n	6.4	22.0
	7.1	21.6
	6.2	25.6
Average	6.7	24.5
Standard Deviation	0.5	2.3

Based on the results, it was found that the hardness of both PLA and ABS are relevant between the range of 0-100 for ABS and 0-90 for PLA (Chohan et al. 2016). Despite being unexpectedly very low in hardness, this is still an acceptable value since the parts are not in their pure dense state, thus the mechanical properties would be different as compared to their respective original, unprocessed material properties in the materials data sheet.

An average reading taken from 5 different points on the sample shows a higher built hardness value (as compared to the respective original materials) in ABS than in PLA, but there are more irregularities in ABS by the higher value in the standard deviation in Table 1.

The hardness of solid PLA materials is about 70-90 (Shore D) and the reading for the printed PLA is slightly 90% lower. A possible explanation for this might be that PLA is a biodegradable thermoplastic, made from renewable resources, and the fact that PLA has a low glass transition temperature. Although this explains why it is easy to print and a suitable material for domestic printers, an implication of this is the possibility that crystallinity occurs in the range of melting temperature, contributing low hardness to the printed PLA. Another possible explanation for this is that the low hardness in the FDM fabrication might also be a result of the presence of gaps inherent in the printing process (Wittbrodt & Pearce 2015). As for ABS, it has no true melting temperature and is a purely amorphous substance.

In terms of durability, ABS, in general, is more durable than PLA because of its high resistance to heat. Therefore, for applications that might be repeatedly twisted, dropped or need to withstand high temperature, it is better to choose ABS over PLA.

COMPARISON OF PARTS SURFACE ROUGHNESS

As shown in Table 2, from the average value, R_a, it can be generally concluded that the ABS part has better surface roughness as compared to PLA.

TABLE 2. Average Surface Roughness R_a for PLA and ABS

		PLA	ABS
	1	1.384	1.607
	2	2.369	1.628
R_a	3	1.213	1.676
	4	2.037	1.684
	5	1.652	1.673
	Average	1.731	1.654
	Standard Deviation	0.423	0.030

Focusing on the roughness consistency along the specimen, as we can see from the very low standard deviation for ABS, it is as expected that ABS has better regularities from the fabrication. In MJP, the resin is later cured using ultraviolet light. In microscale, the process methodology contributed to a better surface roughness in MJP. This consistency may be due to the printing methodology of MJP, where multiple nano jets deposited the resin through one large print head covering the full width of the building platform at each layer, making each layer more uniform.

There is a similar reason for why the roughness of the PLA is slightly higher and irregular, and this is because of the building methodology of FDM, as well as it consisting of line by line of material in each single layer (Szykiedans & Credo 2016). Because of the random deposition pattern in FDM, the direction of the stylus during the test might be transverse with the printing lines making the roughness value higher. In FDM, testing on surface roughness is only conducted on the inside area at 5 different points, where the raster cross-patterned layer after layer as can be shown in Figure 7; the roughness on the cornering points 2 and 4 is higher as compared to the other three points where the patterning is more in straight lines. From Figure 7, ABS has shown better surface roughness and has almost similar readings along the specimen. In one study, experimental results analysis and surface plots led to the conclusion that part build orientation has the most significant effect on surface roughness (Raol et al. 2014).

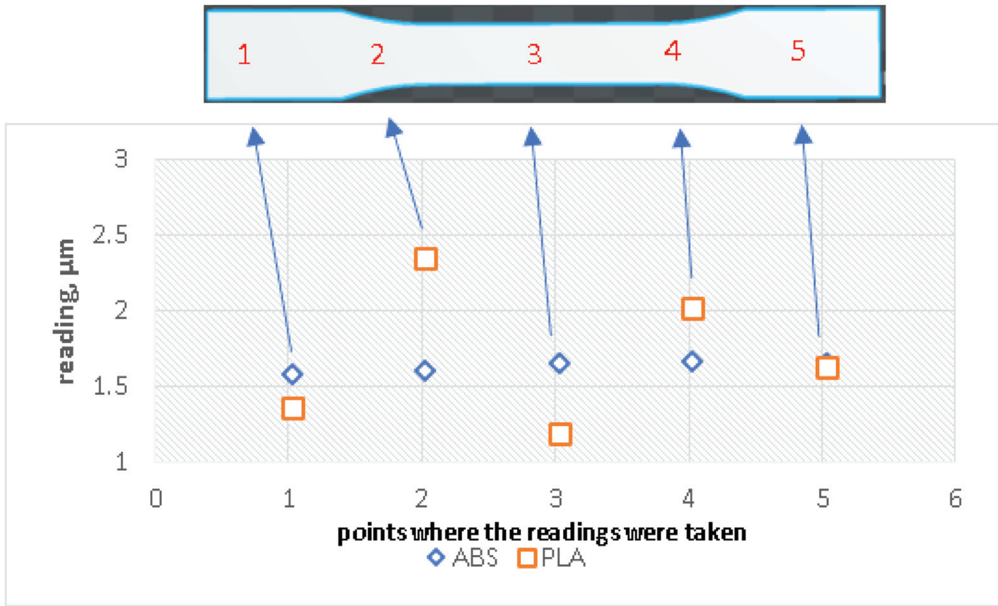

FIGURE 7. Surface roughness reading on different 5 points

For applications that need accuracy, the high roughness of the printed surface may limit the diversification of the application (Farahani et al. 2016). However, for durability and fatigue related issues, it was shown that cracks initiate from the pores inside the core of the specimen rather than from the surface, therefore surface finish alone is insufficient to characterize the durability of the printed parts. This study compares two AM technologies in general. Surface finish is different even based on similar manufacturing techniques (laser based) because of the different laser power, which may cause different powder infusion on the surface (Kumar et al. 2016). High or low surface roughness is important for their future respective applications. There are some applications where a highly rough surface is more favourable. In another research study, it was surprising to find that lower surface roughness specimens show significantly higher fatigue strength (Abele et al. 2015).

CONCLUSION

To conclude, two preliminary qualities, hardness and surface roughness, have been successfully characterised using different printing techniques; MJP technology by 3D Systems using ABS materials has shown better hardness and surface roughness as compared to FDM technology with PLA materials. Based on application, and some optimisation, FDM with PLA is adequate for printing domestic, personal DIY parts. More testing in the future is required to fully understand the mechanical properties of printed parts, particularly to inspect the fatigue and durability qualities

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